

AFRL-SN-WP-TP-2005-109

**THERMAL LENSING IN $\text{Cr}^{2+}:\text{ZnSe}$
FACE-COOLED DISKS**

Jason B. McKay, Won B. Roh, and Kenneth L. Schepler



2003

Approved for public release; distribution is unlimited.

STINFO FINAL REPORT

This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

**SENSORS DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7320**

NOTICE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the Air Force Research Laboratory Wright Site (AFRL/WS) Public Affairs Office (PAO) and is releasable to the National Technical Information Service (NTIS). It will be available to the general public, including foreign nationals.

PAO Case Number: AFRL/WS 05-0480, 25 Feb 2005.

THIS TECHNICAL REPORT IS APPROVED FOR PUBLICATION.

/s/

Kenneth L. Schepler
Principal Scientist
EOCM Technology Branch

/s/

William R. Taylor, Acting Chief
EOCM Technology Branch
EO Sensors Technology Division

/s/

ROBERT D. GAUDETTE, Colonel, USAF
Chief, EO Sensors Technology Division
Sensors Directorate

This report is published in the interest of scientific and technical information exchange and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YY) 2003		2. REPORT TYPE Journal Article Reprint		3. DATES COVERED (From - To) 02/01/2002 – 11/01/2002	
4. TITLE AND SUBTITLE THERMAL LENSING IN Cr ²⁺ :ZnSe FACE-COOLED DISKS				5a. CONTRACT NUMBER In-house	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 61102F	
6. AUTHOR(S) Jason B. McKay and Won B. Roh (AFIT) Kenneth L. Schepler (AFRL/SNJW)				5d. PROJECT NUMBER 2301	
				5e. TASK NUMBER EL	
				5f. WORK UNIT NUMBER 01	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology (AFIT) 2950 P Street 2241 WPAFB, OH 45433				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-SN-WP-TP-2005-109	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Sensors Directorate Air Force Research Laboratory Air Force Materiel Command Wright-Patterson AFB, OH 45433-7320				10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL/SNJW	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-SN-WP-TP-2005-109	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.					
14. ABSTRACT We report the experimental characterization and modeling of thermal lensing in Cr ²⁺ :ZnSe face-cooled laser disks using the phase shift interferometry technique. The thermal lens powers of the 1-mm and 0.5-mm thick disks were strong (37 and 19 diopters at 5 W pumping); the thermal lens power scaled with disk thickness and pump power; and temperatures were reached in the disks at which nonradiative relaxation is significant.					
15. SUBJECT TERMS Rare earth and transition metal solid state lasers, infrared lasers, thermal lensing					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT: SAR	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON (Monitor) Kenneth L. Schepler 19b. TELEPHONE NUMBER (Include Area Code) (937) 904-9661
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			

Thermal Lensing in Cr^{2+} :ZnSe Face-Cooled Disks

Jason B. McKay and Won B. Roh

Air Force Institute of Technology, 2950 P. St., WPAFB OH 45433

jason.mckay@wpafb.af.mil

Kenneth L. Schepler

Air Force Research Laboratory, 3109 P St., WPAFB, OH 45433

kenneth.schepler@wpafb.af.mil

Abstract: We report the experimental characterization and modeling of thermal lensing in Cr^{2+} :ZnSe face-cooled laser disks using the phase shift interferometry technique. The thermal lens powers of the 1-mm and 0.5-mm thick disks were strong (37 and 19 diopters at 5 W pumping); the thermal lens power scaled with disk thickness and pump power; and temperatures were reached in the disks at which nonradiative relaxation is significant.

OCIS Codes: (140.5680) Rare earth and transition metal solid-state lasers; (140.3070) Infrared and far-infrared lasers

Introduction

Attempts to develop Cr^{2+} lasers into usable sources have been hampered by the sensitivity of Cr^{2+} :II-VI materials to thermal distortion [1] and temperature-dependent nonradiative relaxation [2]. Unfortunately, little published data exists on thermal effects in Cr^{2+} doped materials, effectively making Cr^{2+} laser design a lengthy, iterative process, as often the initial design does not work as intended. Recently, we achieved 4.2 W of output in a face-cooled disk laser [3]. Thermal effects were reduced compared to standard bulk configurations but not entirely eliminated. To aid in further power scaling of our disk laser, we measured the thermal effects using a 2- μm interferometer with a phase-shifting technique, then compared the results to modeling using commercial finite-element analysis software. This paper presents the results of that characterization effort and implications for future laser resonator design.

Experiment Overview

The experimental setup, shown in Fig. 1, consisted of a Cr^{2+} :ZnSe disk laser gain head, a Tm:YLF pump laser, a Tm,Ho:YLF probe laser, an interferometer, and a computer for capturing and post-processing the data. The Cr^{2+} :ZnSe gain head itself consisted of a Cr^{2+} :ZnSe laser disk on a water-cooled heat sink, and the associated relay imaging optics used to obtain 16 passes of pump light through the Cr^{2+} :ZnSe disk. Two disks were used in this experiment, a 0.5-mm thick disk, and a 1.0-mm thick disk, both AR coated on the input face and HR coated on the back face (which was attached to the heat sink). The Tm:YLF pump laser produced up to 15 W CW at 1.88 μm , with an M^2 of 5. The multi-pass pumping produced a pumped spot with absorbed power distribution fairly well approximated by a fourth order "super-Gaussian" with 0.4-mm radius. The Tm,Ho:YLF probe laser was of similar design as the Tm:YLF pump laser, but was run with low diode laser input power, resulting in a fairly stable 200-mW output beam at 2.05 μm . This laser was used because the probe needed to be at a wavelength for which the crystals were already coated, and thus more convenient 1- μm or 633-nm lasers could not be used. We used Tm,Ho:YLF instead of Tm:YLF to shift the probe laser wavelength away from the Cr^{2+} :ZnSe absorption peak of 1.75 μm . The probe laser beam was sent through a 1:1 telescope and spatial filter to

clean up the transverse intensity profile of the beam, then run into a Twyman-Green interferometer, configured as shown in Fig. 1. An imaging lens captured the interference pattern and projected it with

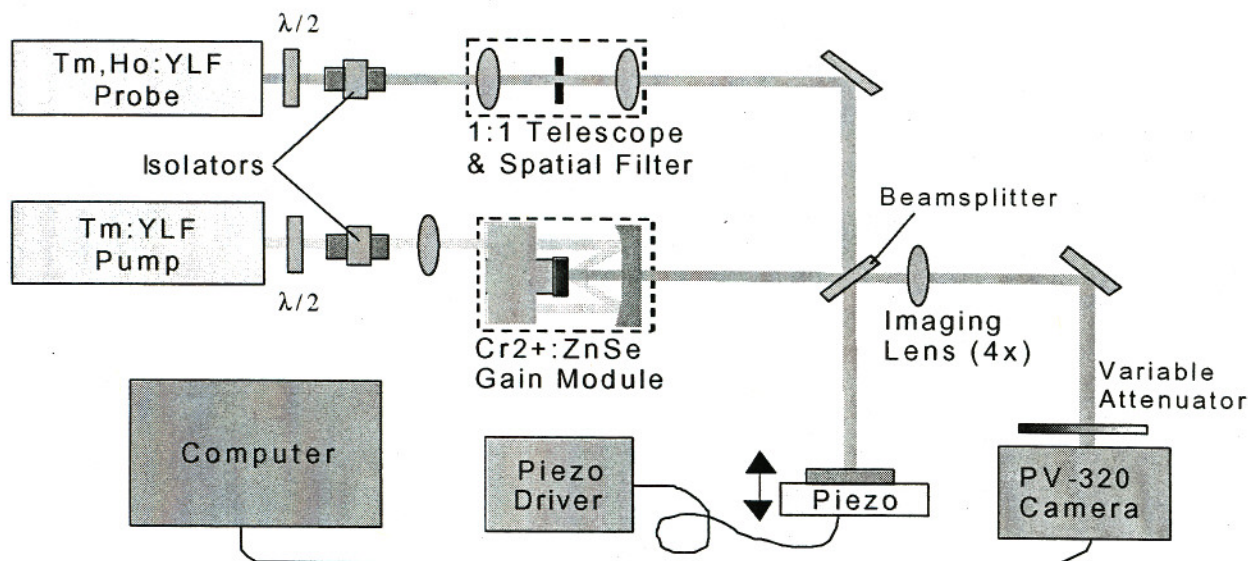


Fig. 1. $\text{Cr}^{2+}:\text{ZnSe}$ Thermal Characterization Experiment Schematic.

4x magnification onto a PV-320 thermal camera. A computer recorded the camera images for further post-processing. By changing the piezo-electric actuator voltage, phase-shifted interference patterns were recorded. The patterns were then post-processed to obtain plots of phase front curvature using standard phase unwrapping techniques [4]. The phase curvature data were then fit to a parabolic surface via least squares analysis to obtain the thermal lens power.

Results

The results of this experiment are shown in Fig. 2. The measured nonlasing thermal lens power in both $\text{Cr}^{2+}:\text{ZnSe}$ laser disks is plotted as a function of Tm:YLF pump power. The results are presented as if the $\text{Cr}^{2+}:\text{ZnSe}$ disks were curved mirrors with lens power ($1/f$) dependent on Tm:YLF pump power. The basic findings are that the thermal lens powers of the 1-mm and 0.5-mm thick disks are strong (37 and 19 diopters, respectively, at 5 W of pump power), the thermal lens power scales with disk thickness and pump power, and fairly high temperatures are reached in the disks.

The thermal lens powers measured in this experiment were initially surprising, as the disk laser concept is supposed to significantly reduce thermal lensing [5]. The experiment showed strong thermal lensing, up to 7 diopters per watt of absorbed pump power for the 1.0-mm disk, and half that for the 0.5-mm disk. The thermal lensing was linearly dependent on pump power, as would be expected. Subsequent thermal modeling showed that since the pump beam radius was not larger than the disk thickness, and since the radial distribution of absorbed pump power in the disks was closer to a Gaussian shape than a "top-hat" shape, our disks did not receive the full reduction of transverse thermal gradients that is the hallmark of the "ideal" thin disk laser design. Transverse thermal gradients did exist, following the absorbed intensity profile, and thus thermal lensing was still significant. One would need to pump at least a 2-mm diameter area on the disk, with a higher order super-Gaussian pump beam to obtain significant reduction of transverse temperature gradients in the disks.

Going to a thinner disk does reduce overall thermal lensing, however, regardless of what the transverse thermal gradients are. Fig. 2 shows this experimentally, with the lens power of the 0.5-mm disk being half that of the 1.0-mm disk. Modeling has indicated that thermal lens power is proportional to disk thickness because the longitudinally averaged temperature distribution in a laser disk is nearly independent of the disk thickness, as long as the total absorbed pump power stays constant and heat loss from the disk edges is negligible. Given that the optical path length scales with disk thickness, but temperature and dn/dT are not affected, thermal lens power thus scales directly with disk thickness. Unfortunately, if one wants to further reduce thermal lensing in $\text{Cr}^{2+}:\text{ZnSe}$ disks by reducing their thickness below 0.5 mm, there is a problem: the 0.5-mm disk was not capable of absorbing much more than 9-10 W in a 0.4-mm radius spot before all the Cr^{2+} absorption was bleached. Going to thinner disks will require more heavily doped crystals, which so far have not been available due to unacceptable losses and high nonradiative relaxation [2].

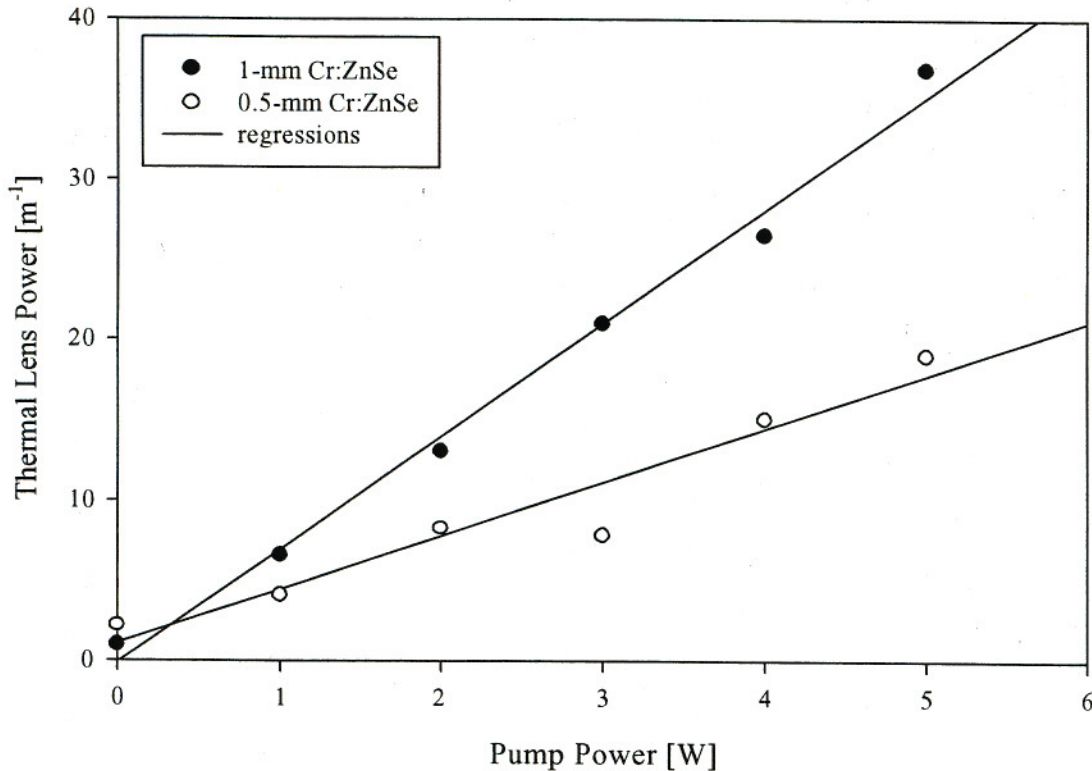


Fig. 2. $\text{Cr}^{2+}:\text{ZnSe}$ disk thermal lensing using 0.4-mm radius pump; 7.0 diopters/watt in 1.0-mm disk, 3.3 diopters/watt in 0.5-mm disk.

Our modeling has shown that overheating as well as thermal lensing must be considered, even in a face-cooled disk laser. Cr^{2+} materials exhibit strong nonradiative relaxation which can significantly reduce the laser gain at temperatures greater than about 50°C [2]. Using the value of dn/dT for ZnSe ($70 \times 10^{-6} \text{ K}^{-1}$) [6] and a plot of phase curvature from the interferometry experiment (not shown), we estimated the longitudinally-averaged temperature of the disk under pumped conditions as a function of

radial position on the disk. The phase difference between the cold edge of the laser disk and the hot center of the pumped spot was measured to be about 20 radians in the 1-mm sample under 5-W pumping. This represents an average temperature along the axis of the pumped region 47 °C hotter than the outside edge. As the heat sink was at 20 °C, the average temperature along the axis of the disk would be 67 °C (estimated temperature going from 20 °C at the heat sink to 94 °C at the uncooled input face). This is hot enough for the $\text{Cr}^{2+}:\text{ZnSe}$ nonradiative relaxation rate to become significant. However, simply cooling down the disk heat sink below room temperature will reduce the impact of nonradiative relaxation.

Summary

Both severe thermal lensing and disk overheating were discovered in our interferometric characterization of the $\text{Cr}^{2+}:\text{ZnSe}$ disks pumped by a 0.4-mm radius multi-mode Tm:YLF laser beam. Thermal lensing as strong as 7 diopters per watt of pump power was measured in the 1-mm disk, and longitudinally averaged temperature rises of ~ 10 °C per watt of pump power were observed at the hottest spot on both disks. Both experimental and modeling results indicate that thermal lensing is proportional to disk thickness and absorbed pump power; but disk temperature is proportional primarily to absorbed pump power and cannot be reduced by using thinner disks. A non-uniform transverse pump intensity distribution will also contribute to thermal lensing. Thus, minimizing thermal lensing effects in Cr^{2+} disk lasers requires the thinnest disk possible, the largest diameter pump beam feasible, and uniform absorbed pump power distribution. However, these steps can reduce laser efficiency so judicious compromises are necessary for optimum performance. Disk heating to the point of increased nonradiative relaxation was also present but can be reduced by reducing the heat sink temperature.

Acknowledgments

We gratefully acknowledge technical discussions with Rita Peterson, AFRL/SNJW, and her detailed review of our interferometry calculations. We also acknowledge financial support by the Air Force Office of Scientific Research.

References

1. Wagner, G. J. and T. J. Carrig, "Power Scaling of $\text{Cr}^{2+}:\text{ZnSe}$ Lasers," *OSA Trends in Optics and Photonics, Vol. 50, Advanced Solid-State Lasers*, C. Marshall, ed., (Optical Society of America, Washington, DC 2001), pp. 506-510.
2. McKay, J. B. and K. L. Schepler, " Cr^{2+} Lasers: Efficient, Broadly Tunable Mid-IR Laser Sources," in *Solid State and Diode Laser Technical Review, DEPS Technical Digest*, 2001, Albuquerque, NM.
3. McKay, J., W. Roh, and K. L. Schepler, "4.2 W $\text{Cr}^{2+}:\text{ZnSe}$ Face-Cooled Disk Laser," *OSA Trends in Optics and Photonics, Vol. 73, Conference on Lasers and Electro-Optics* (Optical Society of America, Washington, DC 2002), pp. 119-120.
4. Novak, J, "Methods for 2D Phase Unwrapping in MATLAB," *Proceedings of MATLAB 2001* (VSCHT Publishing, 2001), pp. 313-317.
5. Erhard, S., et al., "Pumping Schemes for Multi-kW Thin Disk Laser," in *OSA Trends in Optics and Photonics, Vol. 34, Advanced Solid State Lasers*, H. Injeyan, U. Keller, and C. Marshall, eds. (Optical Society of America, Washington DC 2000), pp. 78-84.
6. Page, R. H., et al., " Cr^{2+} -doped zinc chalcogenides as efficient, widely tunable mid-infrared lasers," *IEEE J. Quantum Electron.*, **33**(4): pp. 609-619 (1997).